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The impact of the surface macro-roughness on the surface shear stress and rate under the oblique linear cylindrical nozzle jet as pertinent to particles detachment

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ABSTRACT

Particles mitigation and decontamination by impinging jets is commonly used in various engineering in both indoor and outdoor settings. The current research is concerned with advancing the understanding of the phenomena occurring under the specific linear cylindrical nozzle, as well as under the oblique linear nozzle in general. The numerical method is extensively validated using published experimental data before being applied to the configuration of interest. The results demonstrate large differences between the forward and leeward maximal shear stress and rate at the surface impacted by the oblique jet and the impact of the macro-roughness on their values.

1. Introduction

Impinging jets are frequently used in various engineering systems, such as heat exchanges, drying wet surfaces, coating, or power washing of the contaminated surfaces (Braaten et al., 1990; Gutfinger and Ziskind, 1999; Ibrahim et al., 2004, 2008; Raber et al., 2001; Smedley et al., 2001; Ziskind, 2006). In the center of interest in this study is an oblique linear jet in the context of the re-aerosolization of particles residing on a surface. The jet nozzle is cylindrical, thus the impact of the nozzle body on the flow is small and invariant to the nozzle body orientation. The air flow emerging from the nozzle is directed at the surface at an angle of about 35 degrees from a distance smaller than 0.01 m. Consequently, it is not a free jet, but rather a wall bound impinging jet. The jet velocities range studied and reported here was between 70 m/s and 300 m/s.

It has been reported in the literature that the detachment of particles strongly depends on the surface shear stress (Soltani and Ahmadi, 1995; Young et al., 2013). Experimental investigation of the surface stress under the impact of the jet, even under the most favorable conditions, is challenging. Use of optical methods for example, such as PIV and PDA, requires flow seeding. Particle motion needs to follow the fluid motion with great fidelity to be useful, and thus particles must be very small (on the order of a micron or less). On the other hand, visibility of such particles by the receiving optics in the proximity of the surface illuminated by the PDA laser beam or PIV high intensity pulsed light sheet may become very poor and unreliable. In addition, thermal effects on the surface illuminated by the PIV Nd:YAG laser may alter the near wall flow as well as particle motion significantly. Nd:YAG Laser pulses are known to be capable of removing particles from the surface and surface ablation due to thermal effects.

It is beyond the scope of this paper to expand on a literature review of advances in understanding of planar jets interaction with a wall. Nonetheless some recent examples are provided below. Incomplete similarity for a plane turbulent wall jet is reported in Tang et al. (2015). Typically, a wall jet is divided into two regions: an inner layer and an outer layer. The degree to which these two layers reach equilibrium with each other and produce a self-similar velocity profile is analyzed

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Nomenclature

g_i	gravitational acceleration component in the x_i direction
k	turbulent kinetic energy
l, j, k	directions of the Cartesian coordinate system
u^e	fluid velocity at the fluid boundary of the boundary layer
u_i	i-th component of the fluid velocity vector l – fluid density k – turbulence energy
w	at the wall
x_i	i-th component of the Cartesian coordinate system
y	distance from the wall along the normal to it
y^+	dimensionless distance from the wall along the normal to it
δ_{ij}	Kronecker delta
ε	dissipation rate of turbulence energy
μ	fluid viscosity
μ_t	fluid turbulent viscosity
ρ	fluid density
$+$	parameter is dimensionless on the basis of wall friction, fluid density, and fluid laminar viscosity

using the theory of Barenblatt et al. (2005), which proposes incomplete similarity. This matter is yet to be fully understood. The effects of surface roughness on the mean flow characteristics for a turbulent plane wall jet created in an open channel are described in Tachie et al. (2004). The results show that surface roughness increases the skin friction coefficient and the inner layer thickness, but the jet half-width is nearly independent of surface roughness. Much less has been reported on the oblique jets. Often the area of interest of the interaction of the oblique jet with a surface is approximated by the interaction of the planar jet with a wall. In the research reported here, the entire space between the nozzle exit and the surface is subjected to the numerical modeling. A number of reviews of planar impinging jets both normal and oblique are available in the literature (Looney & Walsh, 1984; Narayanan et al., 2004). Normal planar jets especially have been well investigated (Baydar & Ozmen, 2006; Beaubert & Viazzo, 2003; Maurel & Solliec, 2001; Tu & Wood, 1996; and many others). Somewhat less extensively, the obliquely impinging jets were studied both experimentally and numerically (Akansu et al., 2008; Beitelmal et al., 2000; Chin & Agarwal, 1991; Shi et al., 2003). Many of these studies were performed on aircraft jets in the context of heat exchange and transfer.

This study is intended to specifically numerically investigate boundary flow under a slotted cylindrical obliquely oriented nozzle. The research aims to demonstrate how surface roughness affects the shear stress and rate at the wall.

2. Methods

2.1. Governing equations and solution method

Flow simulation has been used to obtain all relevant flow characteristics. A theory and methodology implemented in flow simulation as described in detail by Sobachkin and Dumnov (2014) is briefly summarized below for the benefit of the reader. Computational domain consists of fluid flow inside and outside the nozzle and inside the enclosure. The boundary condition across the nozzle opening can be defined in terms of flow velocity or pressure. Boundary conditions at the enclosure openings can be defined likewise.

The flow in the computation domain is expected to be turbulent as well as transitional between laminar and turbulent. Turbulent flows are calculated using Favre-averaged Navier–Stokes equations, where time-averaged effects of the flow turbulence on flow parameters are incorporated. In order to achieve closure, fluid state equations supplemented by empirical expressions for density, viscosity and thermal conductivity are added to the system. The adjusted k–ε turbulence model with damping functions introduced by Lam and Bremhorst (1981) can describe laminar, turbulent, and transitional flows of homogeneous fluids simultaneously. It is comprised of the following equations:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho k u_i}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right)+\tau_{ij}^{R}\frac{\partial u_i}{\partial x_j}-\rho\varepsilon+\mu_t P_B \tag{1}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial \rho \varepsilon u_i}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}^{R}\frac{\partial u_i}{\partial x_j}+C_B\mu_t P_B\right)-f_2 C_{\varepsilon 2}\frac{\rho\varepsilon^2}{k} \tag{2}$$

$$\tau_{ij}=\mu,\tau_{ij}^{R}=\mu_t S_{ij}-\frac{2}{3}\rho k\delta_{ij,}S_{ij}=\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k} \tag{3}$$

$$P_B=-\frac{g_i}{\sigma_B}\frac{1}{\rho}\frac{\partial \rho}{\partial x_i} \tag{4}$$

where $C_\mu=0.09$, $C_{\varepsilon 1}=1.44$, $C_{\varepsilon 2}=1.92$, $\sigma_k=1$, $\sigma_\varepsilon=1.3$, $\sigma_B=0.9$, $C_B=1$ if $P_B>0$, $C_B=0$ if $P_B<0$.